DIVISION OF THE HUMANITIES AND SOCIAL SCIENCES

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91125

ADAPTIVE APPROACHES TO THE CO_2 PROBLEM

Roger G. Noll

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ABSTRACT

Scientists and engineers have expressed concern that continued release of CO_2 into the atmosphere from the consumption of hydrocarbon fuels may cause significant, undesirable climatic change, warming the earth's atmosphere by one to four degrees in the next century. This paper is addressed to the issue of developing a way to think about this problem, and a research plan that would most effectively illuminate public policy choices related to CO_2 emissions in the coming decades. Special emphasis is placed on learning more about the responsiveness to drastic changes in economic and environmental circumstances of the industries and localities that are most likely to be affected, and how this responsiveness could be improved by selected government policy actions. Attention is also given to the kinds of scientific and engineering research that would most contribute to society's ability to plan its defense against a prospective man-made change in climate.

ADAPTIVE APPROACHES TO THE CO_2 PROBLEM

Roger G. Noll*

Attempting to assess the likely effects of atmospheric warming due to CO_2 emissions and the possible mitigating actions that could be taken by government is a formidable task. Relatively little is known about the relationship between climate and human welfare; moreover, the problem of forecasting the consequences of a change in climate outside the range of human experiences is extraordinarily complex and difficult. The path that society is likely to follow is to gain more information as time passes, and, as the most probable outcomes begin to emerge, to begin to take actions based upon them. Most of the emissions that will cause the projected atmospheric warming will come decades into the future. Even though many of the possible defensive actions require long-term planning, extensive research, and major new capital investments, there appears to be sufficient time to learn more about the problem before decisions have to be made about taking costly defensive actions. The purpose of this paper is to help formulate a plan of research and information gathering that will allow

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us in a few years to be able to assess more accurately the nature of the problem, and the policy options available to society for attacking it.

STATING THE PROBLEM

The policy-planning problem associated with the CO_2 greenhouse effect can usefully be segmented into three parts. The first is essentially technical: figuring out the likely path of the earth's climate during the next hundred years or so. Current information is sufficient to make us suspect that there is a good chance that substantial atmospheric warming will take place, but we do not know very precisely how much, nor do we have much more than vague hints about the details of climatic change that are likely to come about. Thus, at present society faces numerous possible alternative futures. A central feature of the policy-planning problem is that uncertainty about the technical, scientific aspects of the greenhouse effect is great now, and even with the best research efforts will continue to be significant for years, indeed decades, to come. As long as this uncertainty persists, society is unlikely to make major changes in the economic system or reduce CO_2 emissions or to prepare for a change in climate.

The second aspect of the problem is to examine how the CO_2 buildup is likely to affect human society, assuming that neither national nor international governmental actions are taken to abate or ameliorate the greenhouse effect and its consequences. Initially, this requires examining the sensitivity of the economic system as it is currently constituted to prospective climatic changes. Then, this baseline analysis needs to be refined to take account of the adjustments

that humans are likely to make in economic activities and patterns of population distribution as the climate changes and a new socioeconomic regime takes hold.

The third aspect of the problem is to examine how public policies can generate new, possibly better alternatives than would naturally take place. The policy-planning problem is twofold: one part consists of issues relating to the transition to a new climatic regime, while another relates to selecting--to the extent possible--the new climatic pattern and the socioeconomic system that will in some sense represent the equilibrium adjustment to it.

Because the range of possible climatic outcomes is very wide, analysts cannot now be very specific about the kinds of questions that should be asked in examining the second and third aspects of the problem. For reasons discussed later in this paper, there is little payoff to attempting to figure out optimal agricultural patterns for every climate that might be possible within the limits of current gross predictions in overall warming. As more technical information is gained, some climatic outcomes that are now regarded as possible will be eliminated. This will ease the problem of identifying plausible alternative socioeconomic outcomes and policy options.

Nevertheless, some things can be examined now. These include general methodological--tool building--questions that need to be answered in order to attack more specific questions later. In addition, they include using and expanding available information on the effect of key climatic variables on major climate-dependent activities in order to identify critical ranges or thresholds of these variables that would threaten the viability of these activities or require major readjustments. They also include research on the general issue of the responsiveness of the human institutions that are likely to be affected by climatic change.

Regardless of the actual climatic pattern that may emerge a hundred years hence, to undertake rational policy planning will require some notion of how individual citizens and their organizations will respond to climate change and to government policies that are directed at the problem. The human activities that are most likely to be affected directly by major climatic change are easy to identify: agriculture, energy use, fisheries, water resource systems, tourism, transportation, construction, defenses against diseases and pests, and migration. These are the specific areas in which the responsiveness issues are most germane.

Other research issues cannot be attacked profitably until more information is obtained about the technical issues. In these cases, the value of specific technical research projects is related to the kinds of social scientific and policy research that they make feasible. Hence the selection of technical research priorities should be based in part upon how they are linked to important socioeconomic questions.

Finally, the answers to the technical questions about future climate depend in part on the resolution of other economic and political issues. The pattern of economic development, influenced by policy decisions--especially in energy, environmental, agricultural and water resource policies--will affect CO_2 emissions, and hence the magnitude

of the climate effect, even if no policies are implemented with the CO_2 issue specifically in mind.

The remainder of this paper takes up each of these potential areas of research in more detail.

BASIC RESEARCH IN ECONOMIC THEORY

The first question to be addressed is whether the CO_2 issue raises any special problems that cannot readily be incorporated into conventional economic theory. It would appear that as far as the management of the atmosphere as a resource is concerned, this is not the case. The theoretical challenges have more to do with picking a learning strategy and deciding when (if ever) to take positive defensive actions.

The atmosphere can be regarded as a standard economic resource that enters into production activities and that can be degraded by pollution. At a basic theoretical level, the problem of analyzing an optimal rate of CO_2 emissions does not appear to be different in a major way from other environmental management problems in which the damaging effects of a pollutant are cumulative. Thus, the basic analytical tools developed in the literatures about optimal rates of exploitation of a natural resource[/] and about the problem

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[/] For example, see Partha Dasgupta and Geoffrey Heal, "The Optimal Depletion of Exhaustible Resources," Review of Economic Studies Symposium (1974); and Glenn C. Loury, "The Optimal Exploitation of an Unknown Reserve," Review of Economic Studies 45 (October 1978).

of managing environmental externalities[1] seem to be appropriate

[1] See, for example, R. V. Ayres and A. V. Kneese, "Production, Consumption and Externalities," American Economic Review 59 (June 1969); and David Starret, "Fundamental Nonconvexities in the Theory of Externalities," Journal of Economic Theory 4 (April 1972).

foundations on which to build a conceptual analysis of the CO_2 problem. The thrust of theoretical work in resource economics is to find a time path of the use of resources that maximizes the discounted present value of the future stream of economic output, taking account of some costs, such as environmental degradation, which the normal market system does not take into proper account. Further work that incorporates the special features of the CO_2 problem into this general theoretical framework is justified to be sure that these special characteristics will produce no analytical results that are surprises. Although there are other possible outcomes, the expected result is that, indeed, there will exist an optimal rate of atmospheric warming in the sense of maximizing economic wealth, but that it is less than would occur in the absence of policy interventions. The precise nature of the optimal path of CO_2 emissions will depend upon the details of how the costs of controlling them and the costs of atmospheric warming accrue over time. Thus, to be helpful, extension and adaptation of existing theory should be solidly grounded in the special features of the CO_2 problem.

Recently Heal has begun some work to adapt the standard

theoretical literature to man-made climatic change.[1] While the

[1] Geoffrey Heal, "Interactions between Economy and Climate: A Framework for Policy Design under Uncertainty," prepared for RfF Workshop on the Methodology of Economic Impact Analysis for Climate Change, April 1980.

work shows promise, a central assumption of the model appears to apply to only a limited extent to the CO_2 problem and therefore to risk producing misleading results. The assumption is that atmospheric warming should be viewed as a discrete catastrophic event--that is, that up to some point CO_2 emissions have no effect, and then pass a threshold that causes a climatic catastrophe. The threshold can either be known with certainty, or uncertain but with a knowable probability of occurrence that depends on cumulative CO_2 emissions. While this assumption applies to the possibility of a sudden break-up of the ice shelves of Antarctica, an event that would cause sudden low-land flooding, or to the possibility that there exist thresholds of climatic effects on certain agricultural activities, it does not apply to a continuous relationship between economic effects and the climatic changes that are believed to result from a continuing increase in atmospheric CO_2 concentration.

The obvious next step is to make damage (perhaps stochastic damages) depend on cumulated emissions in a continuous, rather than discrete, way. In addition, the damages could be made to depend on the rate of climate change as well as absolute climate characteristics, representing in a general fashion the possibility that slower rates of change are more amenable to compensating adjustments in productive activities that depend on climate. The literature on the exploitation of renewable resources is also potentially applicable to take account of absorption of CO_2 into the ocean or the biomass should technical research indicate that these effects are important elements in stabilizing CO_2 concentration in the atmosphere through a possible negative feedback effect.

Economic theoretic models of the optimal use of a resource, with or without the possibility of irreversible catastrophes, abstract from one essential feature of the CO_2 problem, that knowledge about the nature of the effect and about ways to adjust to it is likely to improve over time. This creates a decision problem for policymakers that economic theory does not provide a great insight about: when to postpone decisions in order to learn more, when to take action because the risks of further delay outweigh the gains in knowledge that delay would bring, and how to trade off actions to build in flexibility to respond to unanticipated events compared to actions that optimize against the expected state of affairs. Economic theory is likewise unable to provide much insight about how a policymaker should compare differential impacts of change across different categories of people, whether within one country, among several countries, or among generations into the indefinite future. On all of these issues, the best that can realistically be expected from economists is solid empirical work that lays out the range of possible consequences of alternative actions, including geographic and international shifts in

relative wealth that may be potential sources of political and military conflict. It is not realistic to expect of economic theory some new flash of insight about how and when to take global policy actions on the basis of this information.

RESEARCH ON RESPONSIVENESS

In assessing the dimensions of the CO_2 problem, a key issue is the extent to which human society can adjust to dramatic changes in climate. Productive activities that depend in an important way on climatic variables can be regarded as having been designed to produce an efficient transformation of inputs into outputs for a "normal" range of climatic variation. In this sense, technologies have a certain amount of built-in flexibility. However, in organizing productive activities, individual economic agents are likely to find that it does not make sense to take account of all conceivable weather patterns. Some will occur too infrequently or would require contingent plans that are too complex and costly to make it worthwhile to build in some accommodation for them. Individual decisionmakers will elect to make "optimally imperfect" decisions[/] -- that is, to avoid planning for possible situations for which the expected benefit of a contingent coping strategy is small compared to the cost of preparing and implementing it.

[/] William J. Baumol and Richard E. Quandt, "Rules of Thumb and Optimally Imperfect Decisions," American Economic Review 55 (March 1964).

If one studies the effect of a drastic climatic change by examining how a dramatic shift in climate would affect existing activities, the result is bound to overstate the severity of the impact. A change in climate of the magnitude predicted from CO_2 build-up in the atmosphere would alter what is regarded as "normal" variation in the conditions of production, incorporating into this range some conditions that previously were regarded as remote contingencies. When a new definition of normal variation is developed, production methods will adjust (perhaps slowly if new knowledge must be acquired) until efficient technologies are adopted for converting inputs to outputs in the new regime.

The economic effects of a major climatic change can conveniently be divided into three components: the direct impact, the adjustment cost, and the equilibrium effect.

The first component is the direct impact: the effect on economic activity that takes place before economic agents have had a chance to respond. For example, a climatic change that consisted of narrowing the variance of weather about the same mean -- reducing the frequency of extreme conditions -- would probably increase economic welfare in the short run. Eventually, the beneficial impact would be larger, as agents adjusted by avoiding the expense of some of the built-in flexibility of the old methods. Normally, of course, the direct impact can be expected to be harmful. Existing production technologies will tend to be optimized for existing climates, and dramatic changes in climates are unlikely to be as friendly as the preceding example.

The magnitude of the direct impact will depend on the delay

in the response of economic agents to changed conditions. Response may be delayed because agents do not realize a change has taken place, because institutional barriers inhibit a response, or, as in the case of an unanticipated, catastrophic event such as an unpredicted break-up of Antarctic ice shelves, because the speed of the change is faster than any conceivable mitigating response.

Once a response is begun, the second cost is faced, the adjustment cost: the expense of adopting the new modes of economic activity--the investments, the research, etc. Accompanying the investment that is involved in the adjustment cost, but not an element of it, is the loss of wealth that arises from the unanticipated early obsolescence of some capital investments. But it is important to realize that early obsolescence could be a consequence of a beneficial change as well as an unbeneficial one. The new climatic regime could increase the productivity of all climate-related activities, but rearrange the ranking of them in terms of net profitability at a particular locality. In this case, early obsolescence of the old capital and investment in the new would be in response to an opportunity for even greater returns than had been anticipated. The loss of wealth in the old capital would then be more than offset by an increase in the productivity of other resources, notably the locations that had experienced an across-the-board increase in the rate at which inputs could be transformed into outputs. Alternatively, if the climatic change causes an across-the-board decline in net output, the obsolescence effect will be only a part of the loss. In addition, there will be a loss in the productivity -- and hence the value -- of locations that suffer the decline.

The magnitude of the adjustment cost will depend on the speed of the climatic change and the realization that it is taking place. If change is slow and anticipated, investments in new production methods can take place slowly, in tempo with the standard replacement of old capital. These adjustments will be facilitated if the economy is healthy and has well developed capital markets, creating attractive conditions for investments. Adjustments can also be gradual enough to avoid scale diseconomies and bottlenecks in new capital construction and to take advantage of learning curves in new production methods before wholesale commitment to a particular production technology is made. One element of adjustment costs is the mistakes that will be made in finding a satisfactory adjustment to the change.

Adjustments to a new climatic regime can take many forms. One is to reshuffle the geographic distribution of various productive activities. Although this entails no net addition to knowledge about production methods, it does require that some people learn methods that are new to them. In poorer countries with relatively little education, reeducation can be a formidable barrier to adjustment.

In developed societies with relatively high capital per worker, adjustment also entails substantial capital investments to the extent that capital is geographically immobile and is not readily switched from one productive use to another. Neidercorn_/ has examined

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_/ John Neidercorn, "The Capital costs of Climatically Induced Shifts: The Example of the American Corn Belt," in T. Ferrar, ed., <u>The Value Costs of Climate Modification</u>, Wiley, 1976.

an example of one such possibility. He has estimated the capital costs of moving the midwestern corn belt--in response to a cooling of the atmosphere--by figuring out which kinds of capital investments (1) are required for corn, (2) are not required for the crops it would displace in the South or be displaced by in the Midwest, and (3) cannot be relocated at a cost that is less than complete reconstruction.

A second adjustment method is to make a compensating change in production methods for engaging in essentially the same activity. This may involve substantial capital investments, such as the introduction of water storage and irrigation systems in response to reduced rainfall, or it may involve relatively simple changes such as adopting a different seed variety, or changing planting and harvesting dates. As with the first type of adjustment, this is easier in societies with better educational and communications systems.

A third adaptive response is to respond creatively by generating new knowledge about how to make the best use of the new climatic situation. This will involve research expenditures and experimentation, followed by capital investments that are designed to apply the new knowledge, and is therefore most likely to appear quickly in the most developed societies.

The third component of the costs of climate change is the <u>equilibrium effect</u>: the difference in the value of economic output between the use of the old methods in the old climate and the use of new methods in the new climate. Like the other effects, the equilibrium effect can be either positive or negative; there is no particular reason to believe that the present state of the atmosphere is optimal from the point of view of human welfare. Indeed, in extrapolating Neidercorn's analysis, Laurmann has concluded that a small amount of warming would lead to a more productive equilibrium in agriculture,—/ although, as the author states, the conclusion is

—/ J. A. Laurmann, "Assessing the Importance of CO_2 Induced Climate Change Using Risk Benefit Analysis," to appear in Energy-Climate Interactions, Reidel Press.

highly speculative.

Most of the work on the consequences of CO_2 build-up focuses on the equilibrium effect. This may be misplaced emphasis, especially at present, given the enormous uncertainties in any attempt to ascertain what the new equilibrium will be. If, as seems likely, both direct and adjustment costs will begin to be incurred before the new equilibrium is known with much precision, then focusing on how one can adjust to change more expeditiously and efficiently has potentially great payoff. Indeed, if institutional barriers preclude much effective action to prevent climatic change, the value of better knowledge about adjustment possibilities is especially great, and knowledge of the equilibrium effect is valuable only in that it contributes to minimizing direct and adjustment costs.

The responsiveness issue relates to the first two elements of the cost of CO_2 buildup -- the direct impact and the adjustment cost.

Responsiveness refers to the extent to which agents will act to minimize the sum of the direct impact and adjustment cost associated with the change in climate. The importance of the responsiveness issue lies in its relationship to the choice of policy options. Meyer-Abich has usefully classified potential policy responses into three categories: prevention, compensation, and adaptation.—/ Altering his definitions

—/ Klaus M. Meyer-Abich, "Socioeconomic Impacts of CO_2-Induced Climate Changes and the Comparative Chances of Alternative Political Responses: Prevention, Compensation, and Adaptation," Climate Change 2 (1980).

slightly, in the following discussion prevention refers to eliminating or reducing CO_2 production by severely curtailing the combustion of hydrocarbon fuels; compensation refers to massive efforts at technological fixes, such as the deposition of CO_2 in the ocean, major investments in irrigation systems, or a research effort to develop new species that are better adapted to the new climate;—/ and adjustment means relying

—/ For several ideas for technical fixes, see Freeman J. Dyson, "Technical Fixes for the Climatic Effects of CO_2," in Walter P. Elliot and Lester Machta, eds., Carbon Dioxide Effects Research and Assessment Program: Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, U.S. Department of Energy, Document CONF-770385 UC-11: NTIS, May 1979.

on individuals to adapt to climate change without placing special emphasis on this problem other than to facilitate their adjustment. These strategies are not mutually exclusive -- a tax on CO_2 emissions, for example, would probably cause both some reduction in fuel burning (prevention) and some attempts to reduce emissions when fuel is burned (compensation). The choice of a mix of policies among these categories will depend on several things. One is the certainty of undesirable consequences of CO_2 buildup. The massive expenditures required for prevention or compensation are unlikely to be undertaken by government unless the threat of CO_2 buildup is perceived to be both large and highly likely. Moreover, because undertaking these investments will take a long time, the effects of CO_2 buildup are likely to be felt in a major way even if society eventually undertakes prevention or compensation. Thus, some consideration of policies to facilitate adaptation is valuable even in this case, the exact amount depending on the extent to which adaptation can be expected to take place, and on the extent to which government policies to facilitate adaptation can be effective at reasonable cost.

Several useful avenues of inquiry could be pursued now that would be potentially important to policymaking in this area by answering questions about the likely extent of natural adjustment and the costs and effectiveness of policies to facilitate adjustment. The general idea is to examine previous episodes of major changes in the environment in which economic agents have operated. This can be useful not only to gauge the overall or typical patterns of adaptation to changes, but also to examine the effects on the response to drastic changes of differences in the structure of affected organizations, in

the kinds of responses that are called for, in the sophistication of the people involved, in the degree of certainty that a change has taken place, and in the general state of the society -- the health of its economy, its political stability, its level of development.

The kinds of examples of changes that one seeks to study are major alterations in the availability of resources to a large group of people. The inquiry need not be limited to shifts in climate, and indeed these may not be the most interesting cases. Truly long-term shifts in climate are infrequent, and distant historical examples suffer from their questionable applicability to the modern situation and from the paucity of good information about the actual pattern of responses to the change. Studies of recent climatic events--prolonged droughts, catastrophic weather disasters--are of limited usefulness because the changes are not permanent. These represent the extreme contingencies that, before the fact, agents may not find it rational to plan for as completely as they would if these events were more common, and that, after the fact, can be regarded as of too short a duration to warrant a significant response or to be of much value for indicating long-term responsiveness.

The objectives of studies of drastic change should be to improve our knowledge of the responsiveness of human activity to events that are analogous to the CO_2 buildup. It would, incidentally, give some perspective on the magnitude of the CO_2 problem in comparison to other kinds of changes that society regularly faces.

The essential characteristics of the CO_2 problem in terms of the way it will affect individuals appear to be as follows: the effect will be permanent and out of control of individual economic agents; the effect will cause dramatic, unanticipated local changes in the relative profitability of some goods and services; the optimal adjustment strategy is likely to involve major new investments, significant changes in production methods, and the development of new business relations; and at the beginning there may be considerable uncertainty about whether and how the effect has actually been manifested. The fact that the CO_2 problem is related to climate, per se, does not seem to be an essential characteristic at the level of studying the individual responses to the kind of changes that it will cause.

Several types of permanent, dramatic changes could be profitably studied. Agriculture, which probably will be the sector that will be most affected by dramatic shifts in climate, is often subjected to other important changes. A recent example is pesticide bans. One could profitably examine the various kinds of responses--changes in crops, changes in methods of cultivation, switches to other pesticides--made to a banning of a major pesticide, and how the speed and effectiveness of response varied according to the nature of the affected farms (large versus small, family versus corporate). Another example would be major changes in markets for agricultural commodities, such as occur when major changes are made in trade barriers. How did European farmers respond to the development of the Common Market? How have North American farmers responded to the introduction of trade with eastern bloc countries?

The analogy between these events and climate change is as follows. Regardless of the source of change, responsive farmers would

be adopting techniques that were well known to others, but that were new to them. A major new market for agricultural output shifts the relative profitability of various commodities, inducing changes in the pattern of agricultural production and the development of the infrastructure to accommodate the new trade patterns. Climate change would have a similar impact: productivity changes would change the structure of agricultural prices, farmers would change crop patterns, and the markets served by a particular area would be likely to shift. To the extent that climate change did not entail the development of new crop varieties, but represented a redistribution of the patterns of cultivation, the process would be similar. Indeed, if climate change is slow enough, the resulting rates of change in productivity and relative prices might not be much different from the effects of changes in markets and technology that occur for other reasons.

Another potentially fruitful object of study would be changes that directly alter productivity, as would a climate change. An example is the diffusion of major innovations in agriculture, whether the "Green Revolution" in India or the development of hybrid seeds and mechanization in the United States in the last hundred years. The literature on technological diffusion contains several examples of relatively systematic studies of responsiveness. Questions about the likely speed of diffusion in different market contexts and by different types of organizations have been explored, including questions about the role of policy (such as agricultural extension services).[/]

[/] The standard reference on the general question of diffusion is

Edwin Mansfield, *Industrial Research and Technological Innovation: An Econometric Analysis*, Norton, 1968. An especially interesting detailed study is John Tilton, *The Diffusion of Technological Innovation: The Case of Semiconductors*, Brookings, 1972. For agriculture, see Zvi Grilliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* (October 1957), and Charles Rosenberg, "Science, Technology and Economic Growth: The Case of the Agricultural Experiment Station Scientist," *Agricultural History* 45 (January 1971).

Another example of changes that affect productivity directly are changes in the fertility of agricultural regions. One case is the development of major irrigation projects. Another is long-term declines in soil fertility, either because of salt deposits from irrigation as in the Central Valley of California or because of soil-depleting cultivation techniques, especially in less developed areas.

Outside of agriculture, the major sectoral effects of CO_2 buildup generally take the form of major climate-induced shifts in demand. The effects on energy use, public services, water resource systems and transportation, for example, are in large measure questions about the ability of infrastructural sectors to change capacity. The major analogous situations arise in areas that experience large changes in population. The recent depopulation of parts of the Midwest, or rapid population growth in the South and West--especially boomtowns--offer opportunities for studying these adjustments.

In parallel with studies of specific events that might be

analogous to climatic change should be the development of better theoretical understanding of the relationship of organizational structure to responsiveness. Indeed, a continuing interplay between the theoretical and empirical inquiries is necessary for making optimal progress on developing a capacity to evaluate adaptive policy actions.

The literature in organization theory is interesting and provocative, but generally somewhat vague and diffuse. Relatively little progress has been made in generating testable, quantitative hypotheses about the relationships between structure and performance. Nevertheless, some suggestive literature exists on the relationship of special interest here, that between the structure and day-to-day activities of an organization and its ability to adapt to new situations._/

_/ The best general literature on organizations includes James G. March and Herbert A. Simon, *Organizations*, Wiley, 1958, and Peter M. Blau and Richard A. Schoenhen, *The Structure of Organizations*, Basic Books, 1971. Interesting applications to the adaptiveness issue include T. Burns and G. Stalker, *The Management of Innovation*, Tavistock, 1966, Richard M. Cyert and James G. March, *A Behavioral Theory of the Firm*, Prentice Hall, 1963, and Herbert Shepard, "Innovation-Resisting and Innovation-Producing Organizations," *Journal of Business* 40 (1967).

The hope here is twofold: that more adaptive organizations could be established (especially in the public sector), and that government policies could be designed to overcome inertia in private organizations.

The final element of a research program oriented towards responsiveness would be to examine institutional barriers to adaptation--especially political and policy barriers--and policy changes that might enhance adaptiveness. The role of information in a mitigating strategy is crucial, for it is an important determinant of the direct impact costs that arise from delayed response. Policy options should be examined that would permit dissemination of information about the likely future path of atmospheric warming and the range of effective responses that are available. This will facilitate long-term planning by people and organizations who should adjust capital investment plans to the new climatic regime.

Several institutional barriers can retard adaptiveness even in the face of relative good climatic forecasts. One would be the unavailability of credit, especially in less developed countries. Another would be international barriers to migration, or to new patterns of trade that might be developed to take advantage of changing economic potentials in various parts of the world. Still another is price controls, particularly in agriculture and energy, that might interfere with sending decisionmakers the proper market signals about changes in the production costs of different goods and services. The history of the political response of the United States to rapidly rising oil prices in the 1970s is instructive, for it reveals the incentives operating on the political system to retard unexpected shifts in relative prices. Yet, as has been illustrated by the energy problem, price controls in the face of uncontrollable changes in the relative

costs of commodities seriously retard the adjustment of the economic system to economize on the items that have increased in relative cost. A similar situation could arise in the wake of a change in climate, with government intervening to prevent price increases in the basic food commodities that would be adversely affected by the change, and perhaps building price floors (to protect farmers) for commodities that have productivity gains from the climate change. In the energy sector, attempts to hold down the price of hydrocarbon fuels and to subsidize synthetic hydrocarbon will encourage energy consumption and retard shifts to energy sources that do not involve combustion of hydrocarbons, both of which exacerbate the problem of CO_2 emissions.

Nearly every country pursues active pricing policies in both agriculture and energy, so that serious work now on how these policies might inhibit adjustment to climatic change might provide a useful aid to government planning. At the least, such work will provide advance warning about problems that might parallel those that arose after the 1973 Arab Oil Embargo, but that we were not prepared to deal with at the time.

SOCIOECONOMIC CONSIDERATIONS IN TECHNICAL RESEARCH

The principal value of technical research on the atmospheric warming that may occur in the next hundred years is its use for examining the effects on human welfare that climate change will cause. Thus, the selection of technical research strategies ought to be made in part on the basis of the usefulness of the results for long-term economic planning by government entities and by the private sector.

The private sector is often overlooked as a beneficiary of this information, but it, too, engages in long-term capital investments and market planning, perhaps in a more systematic and rational way than the government. If soundly based warnings about climate change are provided long before the change occurs--that is, within the investment planning horizons of private actors--the adjustment costs to change can be greatly diminished. Thus, the following discussion is an attempt to raise some technical research questions that seem especially important to the question of minimizing the costs of the impact of atmospheric warming. By providing this kind of information, society will be able to make a more informed choice among the alternative approaches to the CO_2 problem if such a choice is feasible, and if only adaptive responses are politically feasible, society will be better placed to mitigate the effects.

Because the ultimate concern is not CO_2 *per se*, but atmospheric warming in general, the question immediately arises about the extent to which other man-made emissions may also affect climate, and whether these are as serious--and more or less as controllable--as CO_2. Several other emissions are known to have a similar relationship, within an order of magnitude, between changes in atmospheric concentration and changes in temperature, with some causing cooling and others warming.[/] Indeed, the primary climatic change in the last

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[/] W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo and J. E. Hansen, "Greenhouse Effects Due to Man-Made Perturbations of Trace Gases," *Science* 194, no. 4266 (November 12, 1976).

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four decades has been atmospheric cooling, with some suspecting man-made origins.[/] Work should proceed on the combined effect of all

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[/] M. K. Miles, "Predicting Temperature Trend in the Northern Hemisphere to the Year 2000," *Nature: Climate Supplement* 276 (November 23, 1978).

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important man-made emissions, not just CO_2, to obtain better fixes on future possible climatic regimes.

In undertaking research on climate effects, a necessary input is projections of emissions. For CO_2, this involves projections of the combustion of hydrocarbon fuels; other emissions arise from various relatively well-known industrial sources.

To date, the work on forecasting paths of emissions has not been very sophisticated. A potentially important source of improvement in climate forecasts is to improve emissions forecasts. For fuel, the key question would seem to be the sensitivity of net CO_2 emissions to the assumptions about growth in the total demand for energy and about the mix of energy sources. Thus far, some account has been taken of different splits between hydrocarbons and alternative energy sources, but other issues need to be explored. One is whether there are important differences among hydrocarbon fuels. Some, like coal, are associated with other types of emissions as well, so, in comparison, say, to natural gas, may have a different impact on the atmosphere. Other fuels are from renewable resources--wood, methane from vegetable crops, etc.--which are part of the carbon cycle. What is gained from relying on renewable fuel resources rather than hydrocarbon minerals?

In dealing with the energy sector, forecasts should try to take account of likely future paths of total emissions, and how these are likely to be affected by other policies, especially environmental regulation. In the industrial sector, emissions other than CO_2 probably dominate the picture, and environmental regulation is an even more important element of the forecast. Because of significant differences in emissions from industry to industry, emissions forecasts should also take account of possible shifts in the composition of economic activity.

Of course, reliable point estimates of emissions for decades into the future are impossible. Unanticipated technological changes, discoveries of new resources, and shifts in the pattern of demand among goods will cause massive, probably unpredictable shifts in industrial structure and resource consumption in the next hundred years. Thus, the focus should be on ranges of estimates that are plausible, rather than point estimates.

The kind of research contemplated here must involve both technical experts from science and engineering, who have knowledge about the nature and quantity of emissions that are potentially important in influencing climate, and economists, who can contribute analysis about the paths of economic development that might be followed. Both are necessary to obtain a reliable, long-run assessment of man-made climate change.

Even with the best research effort, however, the dimensions of the greenhouse effect are likely to be subject to considerable

uncertainty for at least three decades and perhaps longer. Effort should be placed on identifying early signals that would enable society to eliminate some possibilities from further consideration.[/] The research would take the form of specific kinds of predictions that deal with necessary precursors to a major warming trend, or that would enable a better judgment about the nature of the warming path that is being followed -- how warm, how fast, etc. Because some adjustments involve long-term capital investments, a steady public release of findings that narrow the range of possible outcomes within the investment planning horizon prior to major warming could be of significant value.

Finally, in projecting future climates, attention should be paid to producing projections on aspects of climate other than hemispheric average temperature changes. Indeed, the most important feature of climate is probably not the mean annual temperature. Among the important features of climate are the frequency and severity of storms, annual rainfall, season to season temperature variance and the length of the growing season, year to year variance (especially in rainfall), and multiyear cycles, including differing sensitivities to changes in solar irradiation, volcanic eruptions, and other relatively long-term factors influencing climate.

[/] For a first look at this issue, see R. Madden and V. Ramanathan, "Detecting Climate Change Due to Increasing Carbon Dioxide," Science 209, no. 4458 (August 15, 1980).

In addition to more detail about dimensions of climate other than mean annual temperature, more detail needs to be provided on a geographical basis. Only when regional predictions are available can the relative merits of different policy options be sensibly compared.

Thus far the attempts to provide some further detail to the predicted effects of atmospheric warming are far from satisfying. One method has been to compare the five warmest years in this century with average years in terms of rainfall and other climate variables.—/

—/ T. M. L. Wigley, P. D. Jones and P. M. Kelly, "Scenario for a Warm, High CO_2 World," Nature 283 (January 3, 1980).

On several grounds this is an inadequate prediction technique. For any given set of background conditions--solar irradiation, atmospheric composition, etc.--warmer temperatures are associated with less stormy periods. Temperature variance within the context of the same background conditions has no necessary connection to a change in mean temperature because of changed background conditions. In addition, annual variations in weather will provide no insight into long-term feedback mechanisms--positive or negative--in the natural system, such as changes in ocean currents and ocean-atmosphere interactions. The equilibrium adjustment to a warming trend could be significantly affected by these secondary effects. Certainly a major research question for the coming decade is to examine the sensitivity of climate forecasts to different assumptions about background conditions and feedback effects, and, if the predictions turn out to be highly sensitive to them, to concentrate

more research effort on incorporating more realistic background and feedback assumptions into climate forecasting models.

Other comparisons have been made with historically distant periods of climate change: the Medieval warm period from 800 to 1200 and the following "little ice age" is one such example, as is the hypisthermal period about 4000 to 8000 years ago.—/ The more distant

—/ William W. Kellogg, "Is Mankind Warming the Earth?" Bulletin of the Atomic Scientists (February 1978).

historical periods make comparisons difficult because of data limitations. Neither the cause of the climate change nor reasonably precise measures of the details of the climate is known.

A high priority item should be to advance technical knowledge about the atmosphere and climate. This will permit more details to be included in forecasts of the impact of the greenhouse effect--particularly the geographical distribution of rainfall, the frequency of weather disasters, and the length of the growing season. This in turn can be fed into the results of research on the effects of various climatic variables on agricultural productivity. Only then will it make sense to investigate in detail the problem of effective adjustment of agriculture to the new climate.

A final matter of detail that needs to be supplied is the likely rate of climatic change. The importance of this knowledge relates to the ability of society to make mitigating adjustments. The more abrupt is the change, the less is the likelihood that society will be able to adjust without suffering a major economic impact, especially if substantial mitigating investments are required to adjust to the new regime. Both politicians and businessmen can be expected to be reluctant to begin to make major investments in new agricultural methods, water resource systems, and energy capacity before there is hard evidence of a warming trend that would justify them. Relatively slow increases in temperature, along with other possible features of the CO_2 effect that can produce the "early warning" predictions mentioned above, will be likely to facilitate this kind of advance planning and investment.

CONCLUSIONS

The key recommendations in this paper are for the kinds of research that will enable us to evaluate a mitigating strategy towards the greenhouse effect--or, indeed, pursue one if massive technical fixes of the preventative or compensatory type prove infeasible. The elements of such a plan are studies about the responsiveness to unanticipated change of the industries and activities that are most likely to be affected, and research that provides more details about the changes they will face, including the path that climate trends will follow and the amount of climate change that can be expected by particular areas and industries.

Some consideration should be given to whether better forecasts of the conditions of the atmosphere ought to be undertaken prior to further attempts to predict the climatic consequences of a change in the atmosphere. The concern is that for a while predictions of

climatic change may be the product of GIGO, in part because only CO_2 is assumed to change and in part because the basis for the forecast of CO_2 emissions is very crude. In any event, the general circulation models (GCM) that are used to predict the effects of CO_2 buildup do not contain very sophisticated characterizations of background conditions and feedback mechanisms, do not produce detailed climatic pictures, and do not give us any clue about the speed and path of change. Thus, the best strategy is probably to emphasize the development of better, more comprehensive atmospheric models that are designed for long-term climate forecasting, rather than to continue to run existing short-term weather forecasting models under a wider array of initial conditions. This is not meant to diminish the contribution of GCM predictions thus far. The GCM has served the important function of making us aware of the possibility of a severe problem, and has given us a long lead time to learn more about the problem and either avoid or cope with it. But to move to a new level of understanding about man-made climate changes probably requires focusing basic atmospheric and climatic research on this particular problem, rather than continuing to borrow from work that was designed to serve an entirely different purpose.

Even if substantial progress is made in improving scientific understanding of the problem, society is still likely to face considerable uncertainty about the magnitude of the CO_2 problem for many years to come. Indeed, if defensive actions are to be taken, there is a good chance that key decisions will have to be made when the range of uncertainty is uncomfortably wide. This suggests focusing research on identifying actions that are most likely to have significant leverage on human welfare: effects which have critical ranges or catastrophe thresholds that are well within the range of uncertainty in climate forecasts, which are not likely to be adequately anticipated and mitigated by private decisions, and which have a high payoff in terms of the possibility that government can be effective in promoting mitigation or prevention of severe consequences.